Published online in 2010 as part of U.S. Geological Survey Scientific Investigations Report 2010-5091.

Integrated Automatic Bedload Transport Monitoring

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Abstract

This paper presents, discusses and compares five different bedload transport monitoring methods. The methods are basically subdivided into three types - quantitative, qualitative and others - and with respect to the gained data into two approaches - Eulerian and Langrangian. Based on investigations in several study reaches, the methods, the measurable parameters and the monitoring results are discussed for basket samplers, automatic bedload traps, an automatic radio-tracking system, automatic geophones and a newly developed sonar system. Each of the presented bedload monitoring methods has advantages and disadvantages with respect to flow disturbance, mobility / flexibility, sample duration, hydraulic and sampling efficiency, grain size determination, transport path, automation and cost.

All five systems are evaluated based on the criteria presented above. The key outcome is presented in the form of two tables. One table underlines the different features of the measurement techniques: negative or positive influences on flow, high or low mobility / flexibility, long or short sample duration, hydraulic and sampling efficiency. Some techniques allow determination of grain size and transport path. Considerable differences are also evident with respect to automation and costs. The second table illustrates the abilities of the various measurement techniques to provide relevant river and transport parameters. This evaluation shows that each system is best suited for a certain parameter or parameter set, but that none measures all parameters with the same quality. The main conclusion is that no single technique yields the necessary and desired measurements. Thus, only a combination and integration of bedload monitoring techniques, depending on the parameters the study intend to analyse, gives an optimal setting. The choice of technique depends on the study aims, river type, available budget, measurement duration and - most important - the parameters of interest.

Introduction

Bedload transport is a fundamental factor in determining the morphologic development of alluvial river reaches. Fluvial problems associated with sediment transport are related to a lack or surplus of bedload and/or to negative influences produced by anthropogenic interference with natural processes (Habersack et al., 2001). Since bedload transport shows a significant spatio-temporal variability (Einstein, 1937; Gomez et al., 1989, Habersack et al., 2001, 2002, 2007, Vericat et al., 2006), the choice of the most accurate measuring system is rather difficult and depends on many parameters.

robust calibration of bedload measuring systems is not possible because no single reference data set exists.

On a worldwide scale, basket samplers are by far the most commonly used type of instrument and have been frequently used in management projects (e.g. Mühlhofer, 1933, Helley and Smith, 1971). Accordingly, one could argue that since a long tradition exists and many researchers have worked with basket samplers, this technique could provide reference data. Examining the hydraulic efficiency of a 152-mm intake Helley Smith sampler for the Drau River in Austria yielded an efficiency close to unity (Habersack et al., 2001). Sterling and Church (2002) showed a clear bias of the bedload samples collected with samplers, including substantial over-registration of sand sizes. Bunte et al. (2004) concluded that Helley Smith measurements were biased, and Vericat et al. (2006) found the probability that a bedload sample collected with the HS152 was biased to be around 43%, whereas 65% of the samples were biased when obtained with the HS76. Bedload traps are increasingly applied in gravel-bed rivers and show improved efficiencies. This reflects the virtual lack of hydraulic influences and the low shear stresses within the trap; high sampling efficiencies are found up to filling stages of 80% (Habersack et al. 2001). Besides basket samplers and traps, acoustic devices, geophones and tracers are also frequently used to measure bedload transport (Chacho et al., 1989, Ergenzinger et al., 1989, Habersack, 2001, Habersack et al., 2007).

This paper compares the accuracies and type of data obtained from individual methods, analyses the advantages and disadvantages of the techniques, and derives a conclusion involving a possible integration of bedload measurement devices to improve overall results.

Bedload transport monitoring methods

Bedload monitoring methods can generally be divided into three groups:

- Quantitative, direct methods
  - basket samplers
  - traps
- Qualitative, indirect methods
  - active and passive acoustics
  - tracers (magnetic tracers can also be used for quantitative studies)
  - other indirect methods, described in U.S. Geological Survey Scientific Investigations Report 2010-5091. (e.g. cameras, impact sensors, radar)
  - Other methods
  - mass balances

In the context of this paper, quantitative methods directly yield transport rates and allow grain size analysis. Qualitative methods, such as acoustics and cameras, require calibration in order to quantify transport measurements. Theoretically, two different approaches for measuring bedload transport exist:

- Eulerian approach
- Lagrangian approach

The *Eulerian approach* considers the transport rate through a defined cross section. This is the most common method of determining bedload transport and is reflected by the long tradition of measuring bedload transport via basket samplers and bedload traps.

Eulerian measurements yield the following parameters:

- Specific bedload discharge [kg m^{-1} s^{-1}]
- Bedload discharge [kg s^{-1}]
- Total bedload transport [kg]
- Spatial and temporal variability of bedload discharge

The *Lagrangian approach* examines particle motion along the river course, for example by using tracer particles (McEwan et al., 2001, Habersack, 2001). Einstein (1937) used a Lagrangian concept as a basis for his transport rate formula when describing the motion of individual particles in terms of step lengths and rest periods.

The Lagrangian approach is mainly used to follow individual particles through their transport path, and the following parameters can be measured:

- Initiation of motion [as a function of e.g. shear stress, N m^{-2}]
- Transport path [m, coordinates]
- Total transport length [m - from erosion to deposition]
- Step lengths and rest periods [m, s]
- Burial depths [m]

Methods

The following sections provide a short overview of techniques used by the author at three integrated automatic bedload monitoring stations on the Isel and Drau Rivers in Austria (see below); they were installed in 2006 (Seitz, 2007). The bedload monitoring stations include:

- Basket samplers
- Automatic bedload traps
- Automatic radio-tracking system
- Automatic geophones
- Sonar

Basket sampler

Measurements were performed using large Helley Smith samplers (Helley & Smith, 1971, Emmett, 1980, Gaudet et al., 1994, Habersack et al., 2001) with a 152 mm intake and 250 µm net mesh. They were lowered from a bridge 8 m above the water level, for example at the station Dellach on the Drau River as part of the integrated monitoring station. Three successive measurements per vertical are made at 10-18 verticals depending on water stage and bedload discharge. Each cross section measurement is repeated twice to account for temporal variations (Habersack, 2001). To improve the temporal analysis, “permanent measurements” are undertaken at a small number of verticals. Measurements are repeated at the same vertical over a period of several hours. Flow velocities are simultaneously measured at a frequency of 2 Hz for 60 to 90 sec with ultrasonic and electromagnetic current meters.

Bedload Traps

Basket samplers allow measurements of bedload discharge with a high spatial resolution; the temporal limitation precludes recording bedload pulsation. Beginning in 1993, a slot sampler, comparable to the weighing slot sampler system (Reid et al., 1980, Laronne et al., 1992, Powell et al., 1995, Garcia et al., 2000, Laronne and Cohen, 1998), was developed and implemented at the Drau River. Based on the results of theoretical considerations and practical boundary conditions, the following two-part system was designed (Habersack et al., 2001):

- A fixed concrete tube of 2 m diameter and 1.5 m depth was installed in the river bed so that the upper part of the concrete tube is flush with the bed.
- Two steel boxes, one located inside the other, can be withdrawn and reinserted into the concrete tube. The steel box has a variable slot opening (Figure 1). A pressure pillow, pressure transmitter and data logger were located between the two steel boxes. Slot width and slot length were 150 mm and 1585 mm, respectively.

In 2006, three additional automatic bedload traps were also deployed at the Drau River. An advantage of one of these bedload traps is that it can be emptied and reinserted even at a water depth of 1m (Seitz, 2007).

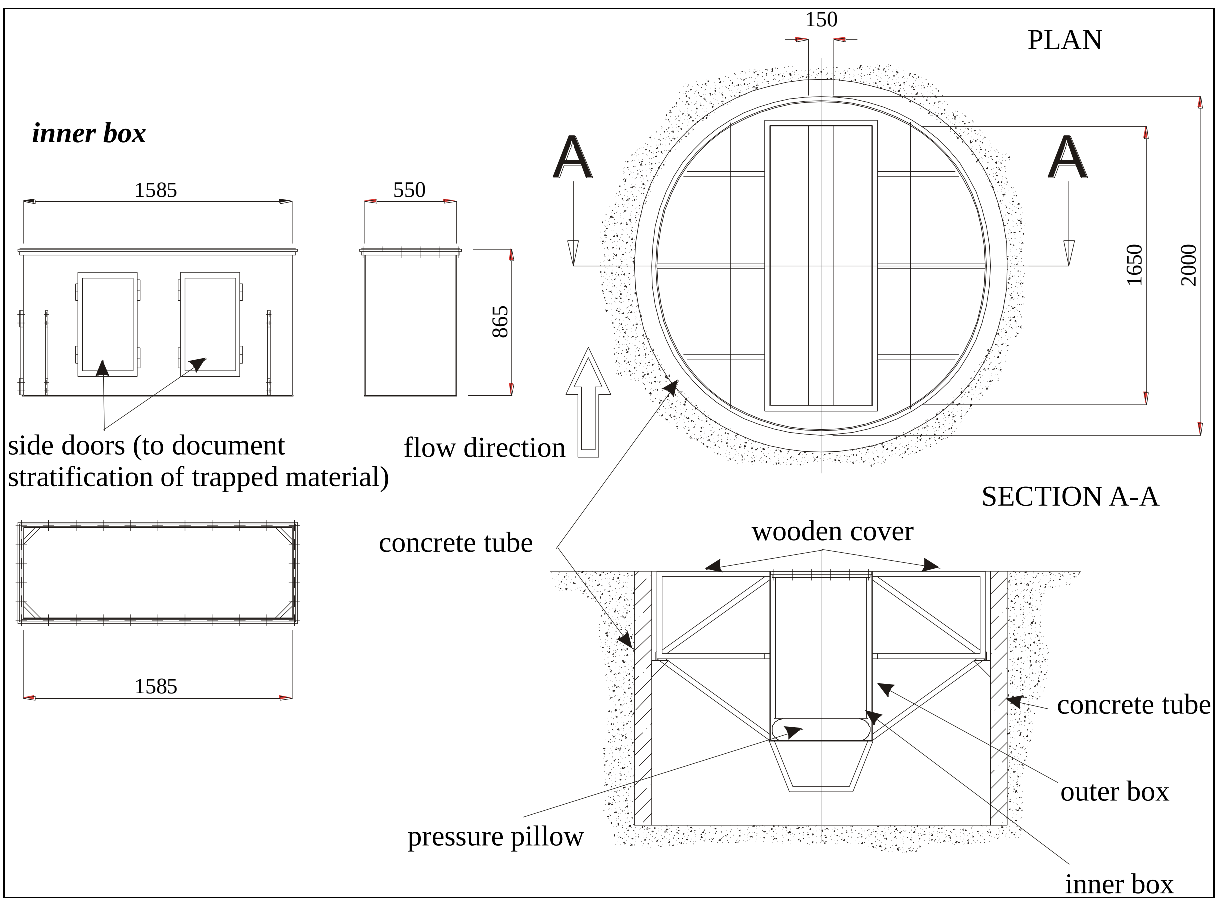


Figure 1. Original bedload trap version for the Drau River (Habersack et al., 2001).

Radiotracers

The use of tracers has a long tradition of usage and has evolved over time. Einstein (1937) used painted particles in the laboratory to observe the flow path of bed particles. Later, radioactive tracers were introduced (Sayre & Hubbell, 1965, Stelczer, 1971). Additionally, fluorescent tracers (Kidson & Carr, 1962) and magnetic tracers (Hassan et al., 1991, Laronne & Duncan, 1992) allowed the total transport rate and burial depth to be measured. The direct measurement of step lengths and rest periods in nature became possible in the late 1980s by using high-frequency radio-tracing techniques (Chacho et al., 1989, Ergenzinger et al., 1989). To evaluate Einstein's model in a field situation, a radio-telemetry system was developed for tracking the path of several gravel particles in the large, braided gravel bed of the Waimakariri River of New Zealand's South Island (Habersack, 2001).

Figure 2 shows the components of this system, which are a transmitter, antennas, cables, switching box, receiver, steering computer, notebook and power supply. Battery-powered radio transmitters are inserted into either natural or artificial gravel particles. The radio signals reach a receiver via antennas, cables and a switching box.

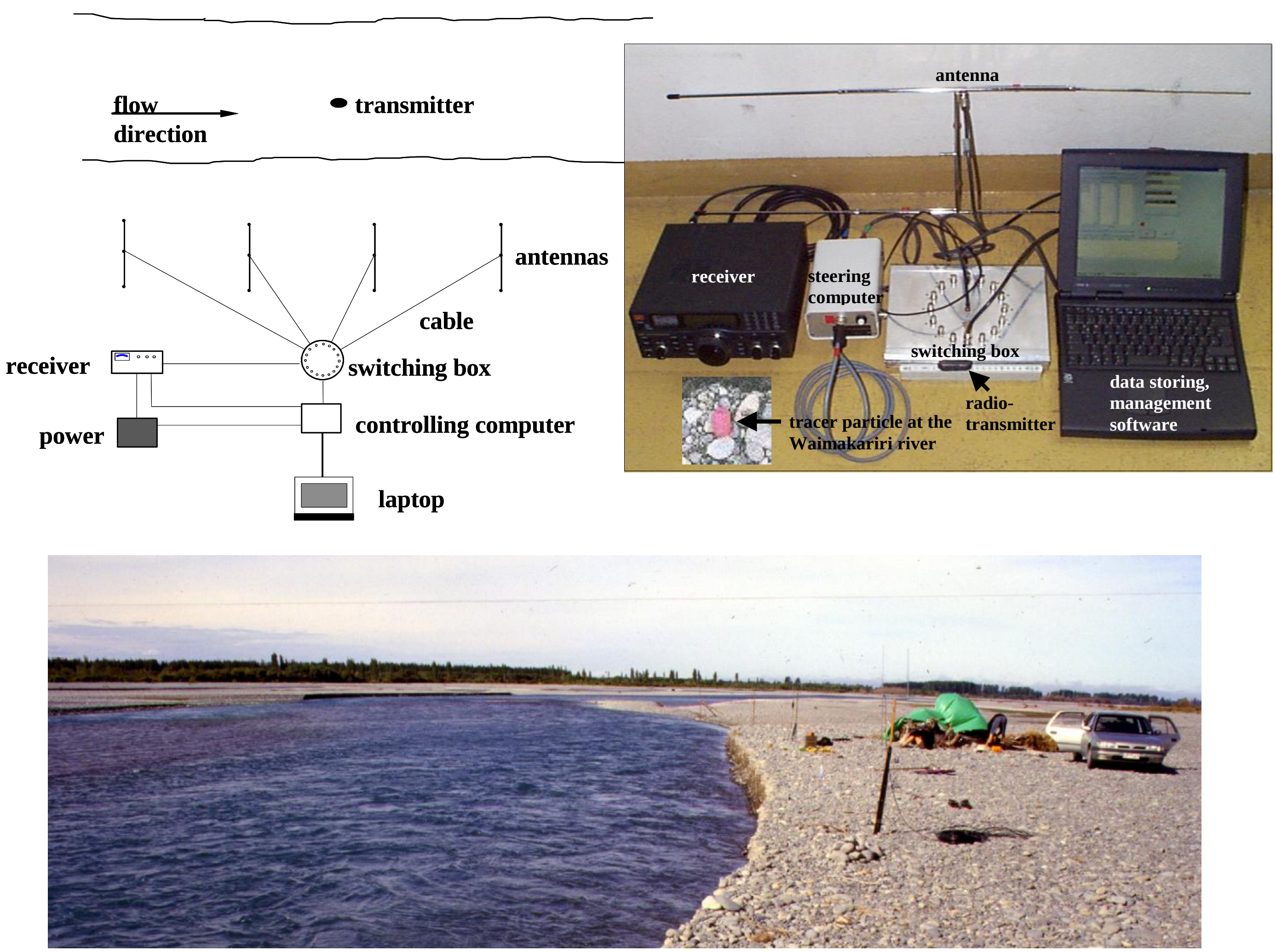


Figure 2. Radio-tracing system (Habersack, 2001).

During transport, the time, number of antenna, frequency, signal intensity and a numerical number defining rest or motion were recorded. Using the intensity of the signal as a function of distance, the position of the stones – along with motion or rest – were recorded. Calibrated nonlinear functions between the intensity of the radio signal and the distance of the marked stones to antennas of known position allowed, for the first time, the path of a stone to be tracked from initiation of motion to deposition (Habersack, 2001). This system continues to be used by an Austrian research group to collect data in Austria, New Zealand and Canada.

Geophones

Geophones are automatic, nonintrusive bedload measuring devices allowing a continuous, automatic measurement - even during large floods (Rickenmann, 1997). In 2002 a station was built in Lienz at the upper branch of the Drau River. In early 2006, two geophone installations were constructed in southern Austria. One was inserted in Lienz at the Isel River and one in Dellach at the Drau River (Seitz, 2007). Today, a system of three gauging stations enables detailed observation of the transport processes and, together with the other monitoring methods, estimates of the bedload budget within the study reach.

Under protection of steel piling, a 2 m high (buried in the river bed) and 1 m thick armored concrete barrier was constructed across the entire cross section of the river, following its profile (Figure 3). The geophone plates (width 50 cm, length in flow direction 36 cm) were mounted on top of the barrier to slightly extend above the riverbed (max. 10 cm) to avoid silting of the measurement device. Downstream of the barrier we installed bed-load traps (Figure 3). The geophones were distributed across the channel at 1 m intervals in the deeper parts and at 2 m intervals in the shallow part. In total, 40 water-proof geophones were deployed at Dellach, 32 at Lienz, reflecting the differences in river bed width (50 m at Dellach, 40 m at Lienz).

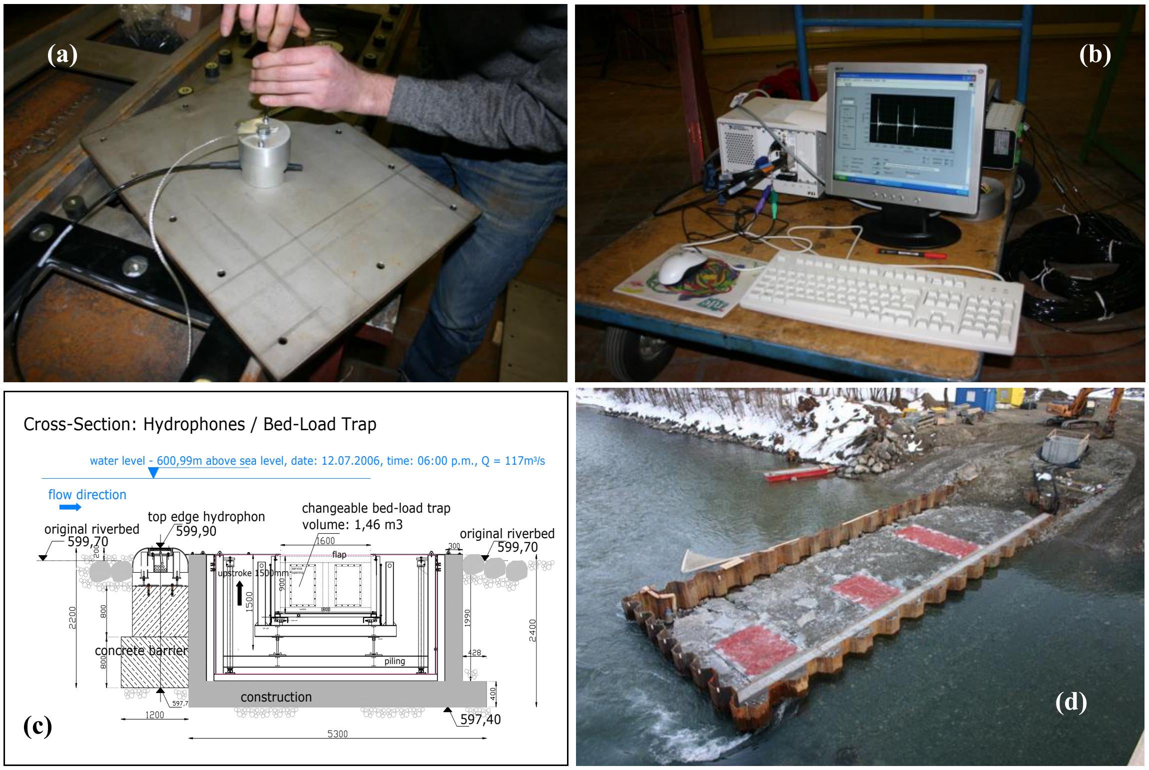


Figure 3. Geophones mounted on a steel plate (a), operating system (b), measurement system with geophones and bedload trap (cross view, c), construction of geophones and bedload traps in the Drau River under protection of steel piling, Seitz (2007) (d).

The geophones were connected to a PXI Industrial Personal Computer equipped with measurement reading cards. The geophones were sampled at 2000 Hz. Every stone passing the steel plate with a geophone mounted generates an impulse. An A/D converter processes the information. A data acquisition application, written with LabView©, controls the sampling. Using a calibrated voltage-exceedance threshold scheme (user defined, 0.1 V in 2006) grain impacts are recorded and counted.

Counted impulses per minute, the maximum amplitude per minute and cumulative integrals of the pulses (for special purposes it is also possible to save impulses per second) are stored. The system enables the user to watch the generated impulses on the computer screen (Figure 3). The system can be operated and monitored remotely using a GSM (Global System for Mobile Communications) modem. SMS (Short Message Service) alarms are generated from the system in case of power failures (batteries can supply the system with power for 24 h) or flood events. Most of the other data sets (river gauging etc.) can also be transmitted via the GSM modem.

Sonar

To investigate if sonar may also be used to track bedload transport in a gravel-bed river, we used a sonar system known as ADMODUS. This consists of several devices attached to an equipment rack (Hydrografic Service GmbH, 2006). This prototype instrument enabled us to simultaneously measure numerous parameters (flow velocity, suspended sediment concentration and shear stress) that influence bedload transport from nearly the same position above the river bed. The first device is the AdmodusFlow©, which measures near-bottom flow velocity in 16 ground-parallel gates. The non-contact device AdmodusSonar© quantifies bedload transport by comparing repeat scans. Suspended sediment concentration is measured using an ultrasonic backscatter unit, grain and rack movements are monitored by a video camera, and a global positioning system is used to locate the device. Declination sensors and attached compasses provide exact placement on the river bed. In the future, a basket for bedload collection and a device for direct shear stress measurements will be attached. Figure 4 shows the equipment rack with the attached devices during sampling.

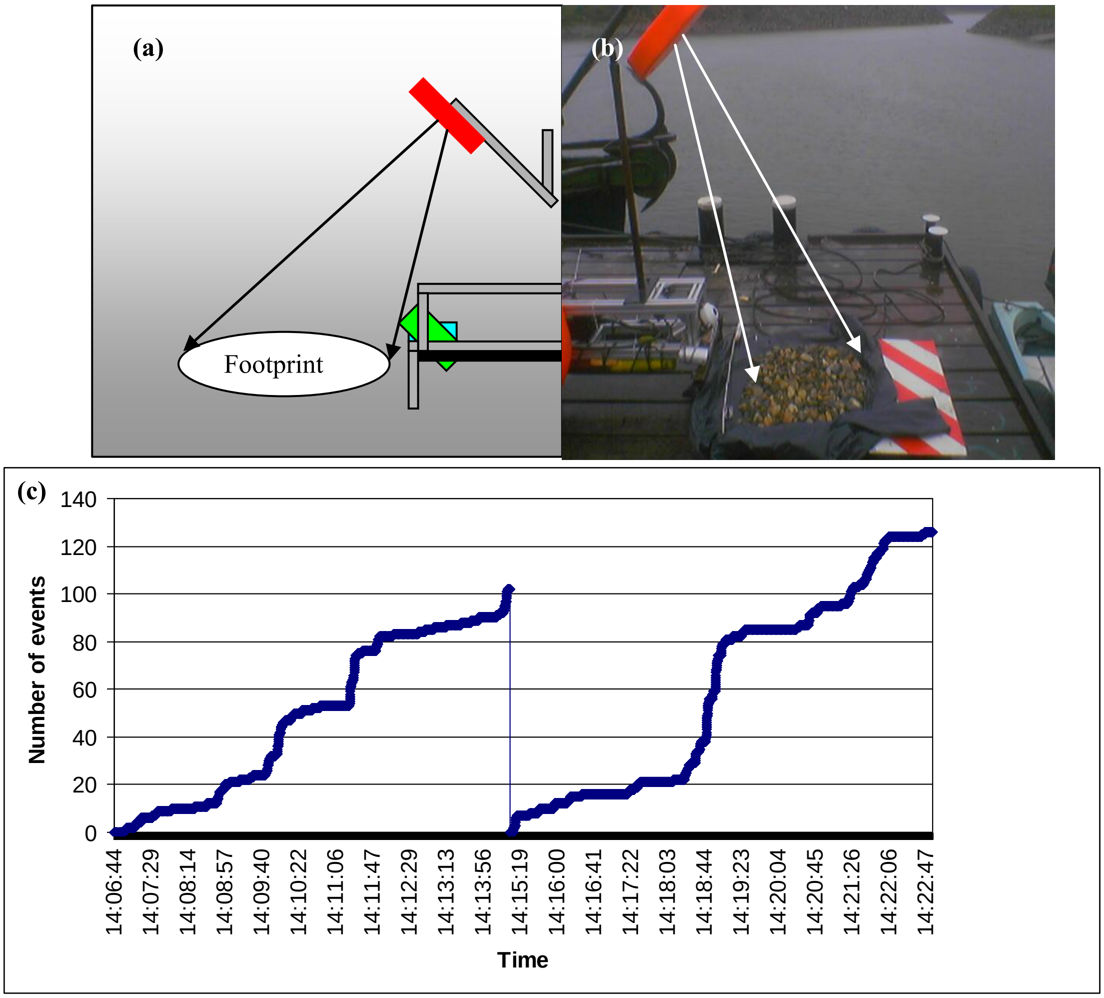


Figure 4. Admodus equipment rack (a), monitored area of the AdmodusSonar© (b), bedload monitored by using the 210 kHz converter (c) (Hydrographic service, 2006, Liedermann, 2007).

In the following, only the AdmodusSonar© is described more precisely:

AdmodusSonar©

The AdmodusSonar© device is normally deployed to map riverbeds from watercraft sweeping up and down the river. Typical frequencies range between 12 kHz and 3 MHz (Gamnitzer et al., 2006). Sonar technology assumes that a ship moves while measuring a static bed. The AdmodusSonar© uses the device in the opposite manner. To measure bedload transport, the sonar is stationary but the bed moves. If there is no transport, the sonar picture remains unchanged and no transport is detected. If the riverbed changes, the gathered image will be different and a bed movement will be recorded. At no movement, the similarity between the two reflected signals is a maximum and the correlation coefficient is 1. When single stones move, the pattern of the reflected signals changes, which reduces the correlation coefficient. The decrease in similarity is proportional to the quantity of stones changing their position. If the similarity function falls below a certain threshold (calibration parameter), a bedload-transporting event is recorded and the new picture is taken as a reference. The number of events is non-linearly proportional to bedload transport rate.

The resolution of the ultrasonic converter depends on the wave length used. The Admodus device uses two different wave lengths - each of them optimized for a certain grain size range. The echo signal of the low frequency converter (38 kHz) is dominated by larger gravel, whereas the 210 kHz converter (wave length 7.5 mm) also detects smaller sized gravel.

Study reaches

The integrated automatic bedload monitoring stations are installed at the Isel River and Upper Drau River upstream of Lienz in Eastern Tyrol, Austria, and at the Drau River at Dellach in Carinthia, Austria. At Dellach the Drau has a bed width of 50 m (for mean discharges), a longitudinal bed slope of 0.18 percent, and a subsurface mean grain diameter of 32 mm at the monitoring site. The mean annual discharge is 64 $m^3 s^{-1}$. The Drau is glacier-meltwater-fed during spring and summer. Minimal flow depth and velocity are 0.6 m and 1 $m\ s^{-1}$, respectively. The monitoring site at the Drau River drains a basin area of 2561 km^2 (at the Sachsenburg gauging station). In addition to bedload monitoring, suspended load measurements, continuous flow velocity measurements and temperature measurements are performed. The Admodus instrument is located on the Danube River, downstream of Vienna, and is currently being used in an integrated river engineering and restoration project (Habersack et al., 2007). The radiotracers were also used outside of Austria in New Zealand (Habersack, 2001) and Canada.

Results

Basket sampler

Helley Smith sampler measurements have been performed at the Drau River since 1992. This sampling effort has provided a variety of results that include the spatio-temporal variability of bedload transport, textural analysis with preferential transport of gravel-sized fractions, and an evaluation and improvement of bedload discharge formulas (Habersack et al., 2001, 2002, 2007).

Traps

The in situ test of the hydraulic efficiency of a slot sampler showed that the hydraulic efficiency is greater than 90 percent up to and including 60 percent fill. At 80 percent fill the hydraulic efficiency is 66 percent. The sampling efficiency was close to unity (Habersack et al., 2001).

The one-hour temporal variability of bedload flux is shown in Figure 5. The bedload waves clearly occur with distinct peaks up to a maximum of 0.064 $kg\ m^{-1}\ s^{-1}$ (beginning of snow melt season, weak transport).

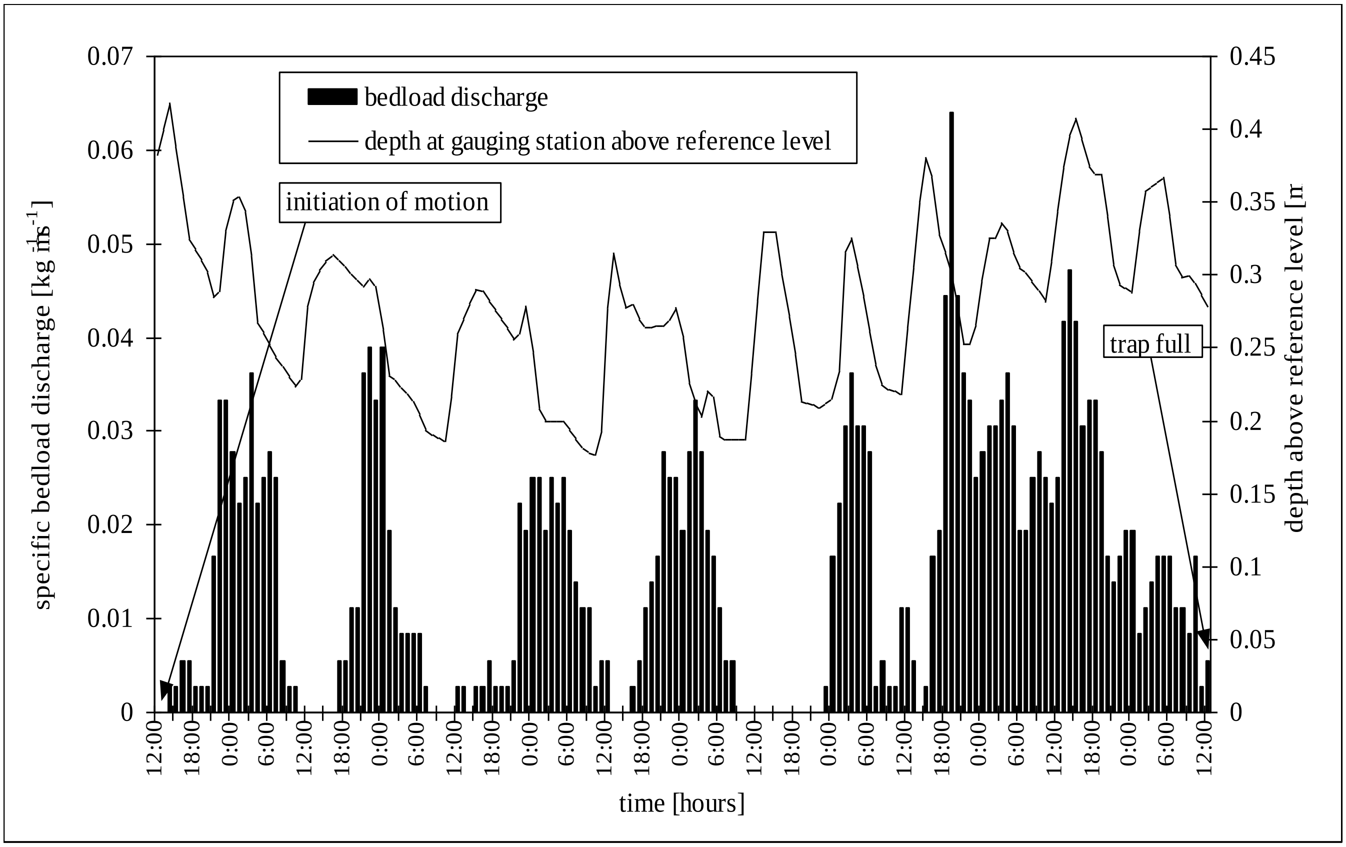


Figure 5. Temporal variability of bedload transport, measured with bedload trap (Habersack et al., 2001).

One explanation for the temporal variation is that a significant surge effect acts at the Drau, leading to a 0.15 m daily variation in the water level. Because shear stress is close to the critical shear stress during this period of the year, the small increase in discharge (and water depth, as shown in Figure 5) is sufficient to initiate weak bedload transport.

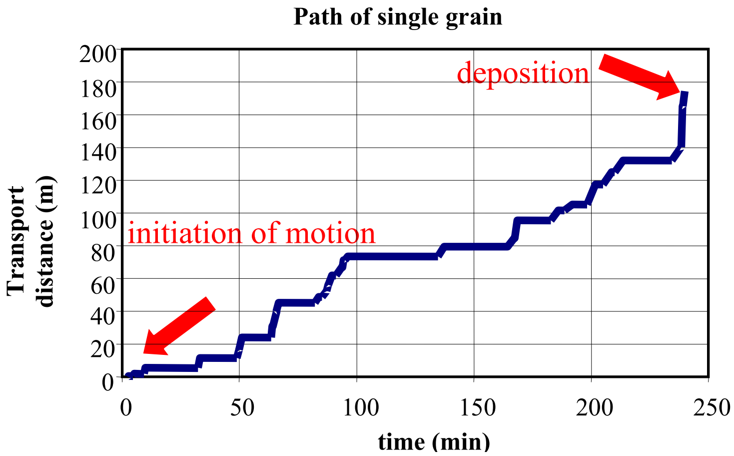
Several advantages of slot measurements compared to the basket sampler results have been identified for Alpine gravel bed rivers:

- automatic and continuous measurement of bedload transport over lengthier periods,
- accurate determination of initiation of motion, and
- detection of the temporal variability of bedload.

Radiotracer

The first two areas of measurements with active tracers were in Germany at the Lainbach (Ergenzinger et al., 1989) and in the USA / Alaska (Cacho et al., 1989). In 1997, field tests with an improved system started in Austria (Habersack, 1998). From December 1998 to May 1999, an intensive field campaign was performed at the Waimakariri River in New Zealand (Habersack, 2001). In 2003, measurements were conducted at the Sunwapta River in the Canadian Rockies.

At the 1 km wide braided section of the Waimakariri River at Crossbanks, New Zealand, the transport path of individual, artificially produced gravel particles was monitored during various floods of different magnitude (Figure 6).



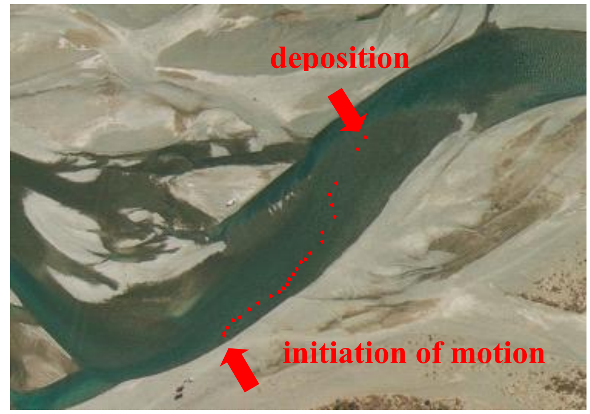


Figure 6. Results of radio tracking bed particles in the Waimakariri River in New Zealand (Habersack, 2001).

Rest periods followed an exponential distribution, whereas step lengths were modelled by the use of a gamma distribution with the density function (Habersack, 2001). Furthermore, an in situ analysis of the interrelation between pressure fluctuation / lift forces and initiation of motion provided insight into this key bedload transport process (Smart & Habersack, 2007). The following conclusions regarding the use of radio-tracking were derived:

- Radio-tracking of gravel particles can confirm the stochastic nature of bedload transport even at large braided rivers;
- Initiation of motion can be related to pressure fluctuations;
- The flow path of individual particles can be traced;
- Field data for comparison with discrete particle modeling techniques and stochastic modeling approaches are given; and
- Important facts for morphological questions can be analyzed (distances from erosion to deposition, effects of different floods, different river morphologies, etc.)

Geophones

The geophone system has been operating since July 2006. So far, only small floods occurred and the calibration is still ongoing. The measurement devices are now fully equipped and ready for the next summer seasons. Figure 7 shows the spatio-temporal variability of bedload flux with an increasing bedload discharge from the banks towards the centreline of the river and some periodicity of bedload flux over time.

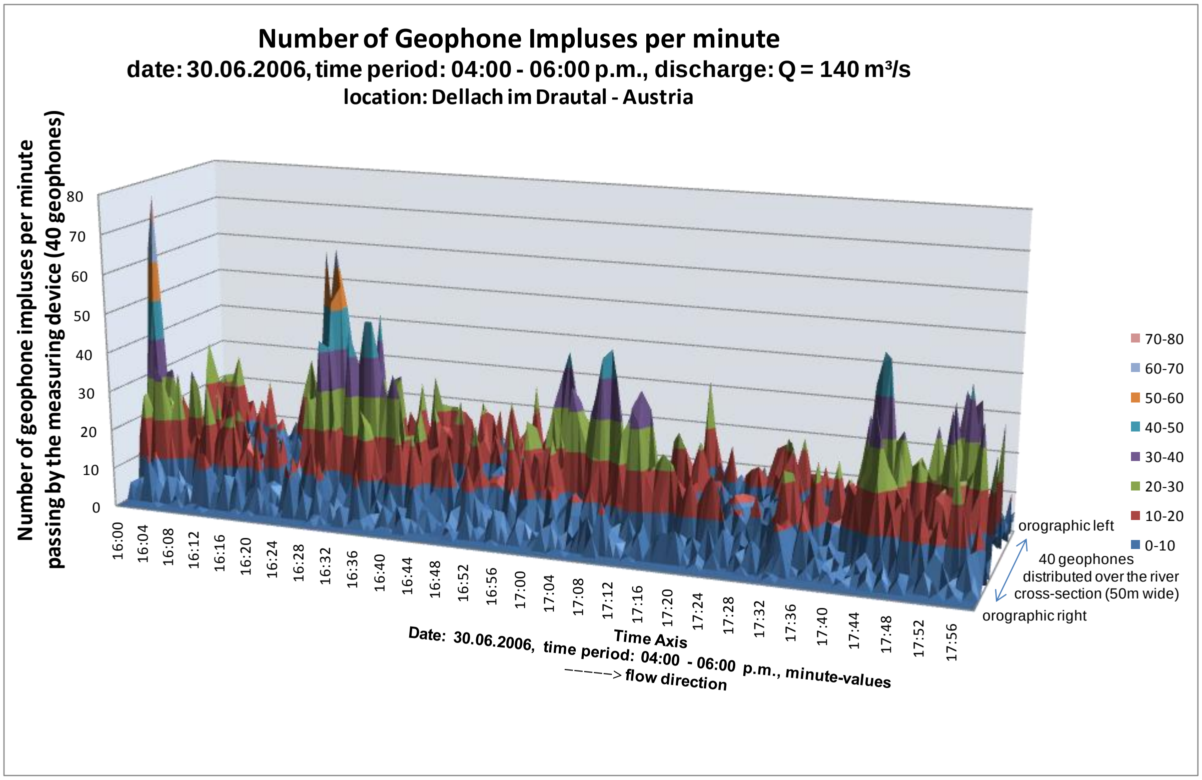
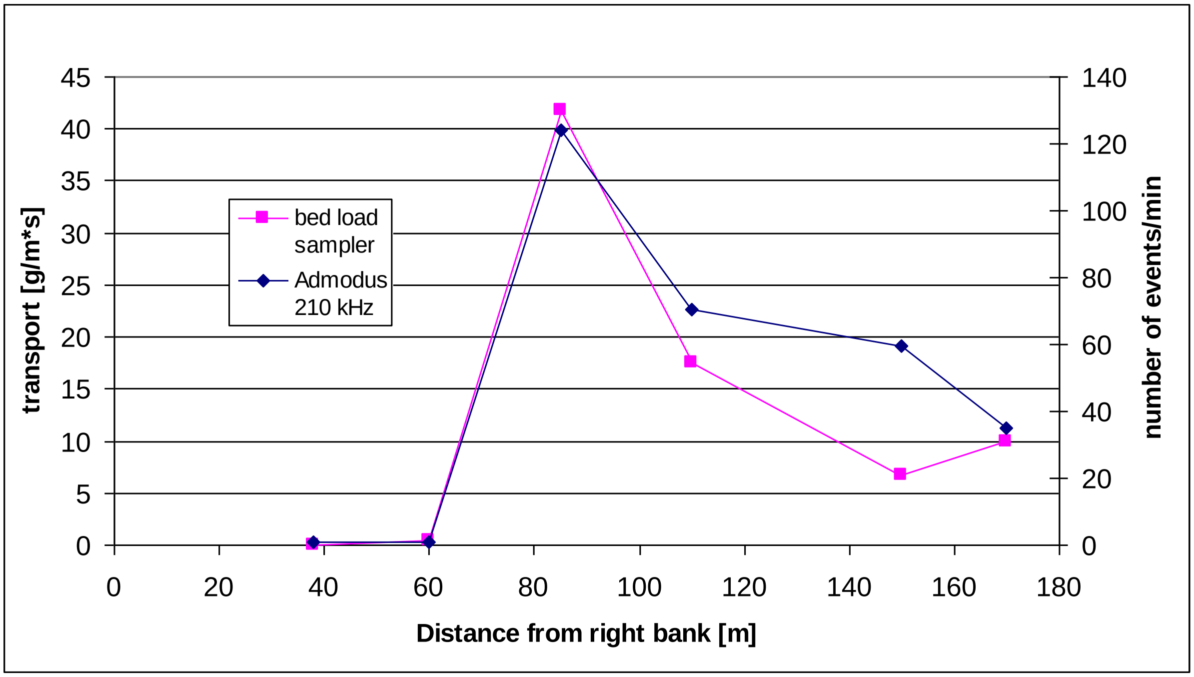


Figure 7. Time series of geophone impulses over the cross section at Dellach (Seitz, 2007).

Sonar

The results of the ADMODUS measurements are discussed for one cross section of the Danube River and compared to the measurements of a basket sampler used at the same time and place. To determine whether the two devices provide comparable results, the transport rates have been plotted in Figure 8.



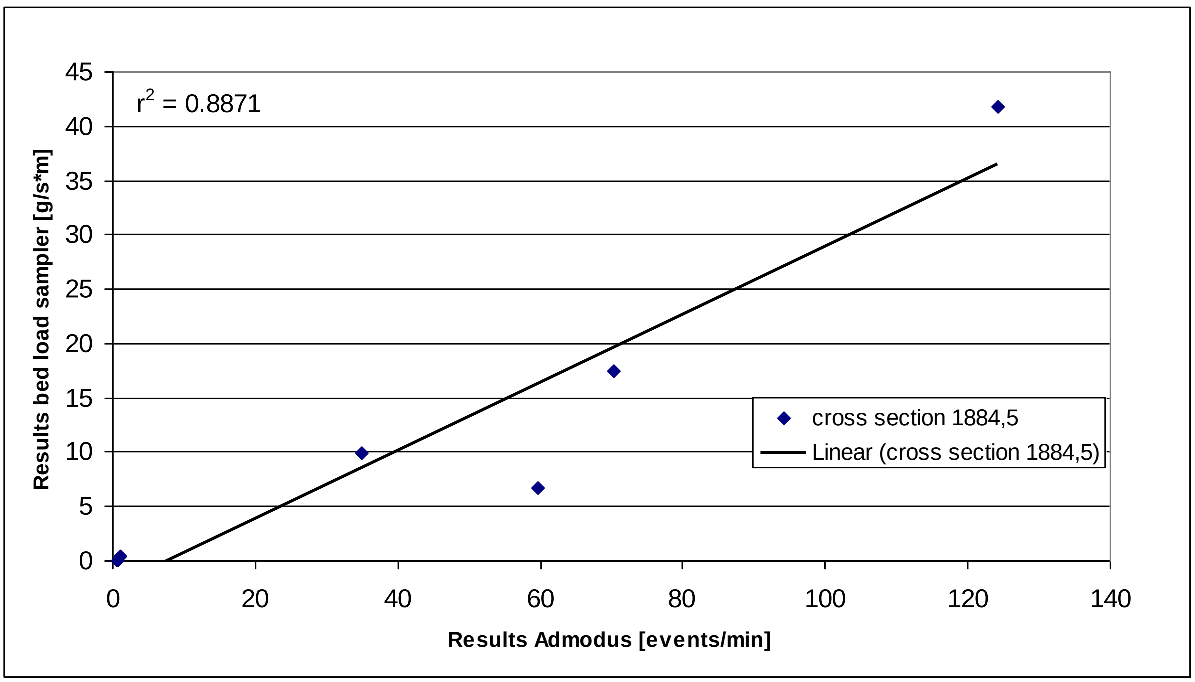


Figure 8. Comparison of (a) bedload transport by basket sampler and Admodus (210 kHz) and (b) correlation of basket sampler results with Admodus (210 kHz).

The transport rates of the basket sampler match the tendency of bedload transport surveyed with the Admodus 210 kHz converter quite well. Calibration work in a hydraulic laboratory and in the field by applying a sampler immediately downstream of the Admodus "footprint" will be performed to calibrate ADMODUS measurements.

Figure 8b compares the results from the two devices and illustrates that there is a good agreement. The ADMODUS will also be implemented at the Drau River monitoring stations.

Discussion

Each of the presented bedload monitoring methods is characterised by inherent specifications and shows advantages and disadvantages with respect to the following criteria:

- Flow disturbance
- Mobility / Flexibility
- Sample duration
- Hydraulic and sampling efficiency
- Grain size determination
- Transport path
- Automation
- Costs

The *flow disturbance* results from the fact that basket samplers, for example, must be lowered to the river bottom from bridges or ships and, being flow intrusive, interact with the flow. Thus, basket samplers cause local hydraulic changes by increasing roughness and, as an obstacle, disturb both the flow field and gravel transport (Habersack et al., 2001, Vericat et al., 2006).

Mobility and flexibility describe the ease of change in position and adaptation to changing boundary conditions (e.g. bed level changes).

Sample duration is crucial in obtaining representative samples regarding the temporal variability of bedload flux. A high hydraulic and sampling efficiency is the prerequisite for obtaining reliable bedload transport data. The grain size determination is important for any engineering and modelling applications of the measured data. Knowing the transport path of particles allows an analysis of the interaction between sediment transport and river morphology. Automation is essential for a sustainable and cost-effective use of bedload monitoring devices because floods occur often during the night. The costs of the measuring device determine how likely the device will be implemented in a regular hydrographic monitoring program.

We summarize our observations by evaluating the five systems based on the above criteria, using a seven value classification: three positive influences (+ slightly positive, high, ++ positive, high, +++ significantly positive, high, three negative influences (- slightly negative, low, -- negative, low, --- significantly negative, low) and a neutral class (+-). Table 1 shows the results of our evaluation. Clearly, the different measurement techniques negatively or positively influence flow, show high or low mobility / flexibility, entail long or short sample duration, and have different hydraulic and sampling efficiencies. Some techniques allow grain size and transport path to be determined. Considerable differences are also evident with respect to automation and costs.

Table 2 illustrates the abilities of the various measurement techniques to provide relevant river and transport parameters. This evaluation shows that each of the systems is best suited for a certain parameter or parameter set, but that none measures all the parameters with the same quality.

Table 1. Advantages and disadvantages of bedload monitoring methods with respect to relevant criteria.

Method	Flow disturbance	Mobility/ Flexibility	Sample duration	Hydraulic and sampling efficiency	Grain size determination	Transport path	Auto-mation	Costs
Basket sampler	---	+++	--	--	+++	---	---	-
Trap	+-	---	++	+++	++	---	++	--
Radiotracer	+-	+++	++	+-	+++	+++	++	-
Geophones	-	---	+++	+-	---	---	+++	---
Sonar	-	++	+++	+-	---	+	+	-

+++ significantly positive, high
++ positive, high
+ slightly positive, high
+- neutral, no effect, unknown
- slightly negative, low, low costs
-- negative, low, medium costs
--- significantly negative, low, high costs

Table 2. Suitability of bedload monitoring devices concerning specific parameters.

Parameters	Basket sampler	Trap	Radiotracer	Geophones	Sonar
Specific bedload discharge [kg m^{-1} s^{-1}]	●●●	●●●		●	●
Bedload discharge [kg s^{-1}]	●●●	●		●	●
Total bedload transport [kg]	●●●	●		●	●
Spatial variability of bedload discharge	●●		●	●●●	●●
Temporal variability of bedload discharge	●	●●	●	●●●	●●●
Initiation of motion	●	●●●	●●●	●●●	●●●
Transport path [m, coordinates]			●●●		
Total transport length [m - from erosion to deposition]			●●●		
Step lengths and rest periods [m, sec]			●●●		
Burial depths [m]			●●●		

●●● highly suited for measuring this parameter
●● suited for measuring this parameter
● partially suited for measuring this parameter
not suited for measuring this parameter

Conclusions

This paper describes five specific bedload monitoring methods and, based on extensive experience and field implementation, compares the methods to one another. The main conclusion is that no single measurement technique alone yields the necessary and desired data for all parameters. Thus, only a combination and integration of bedload monitoring techniques, depending on the specified parameters, provides the optimal approach. The choice of technique depends on the study aims, river type, available budget, measurement duration and - most important - the parameters of interest.

Future work will involve further calibration of the geophones and sonar system using the bedload trap and basket sampler measurements. The main focus will be on a comprehensive analysis of the spatio-temporal variability of bedload transport based on the integrated automatic monitoring stations.

Acknowledgements

The authors thank the Austrian Ministries of Agriculture, Forestry, Environment and Water Management, Infrastructure and Technology (BMVIT), viadonau and the states of Carinthia and Tyrol for supporting these bedload monitoring activities. Many thanks go to both reviewers of this paper, Andre Zimmermann and Jeff Marr, for their important and constructive remarks, also to Jonathan Laronne for his helpful comments.

References Cited

Bunte, K., Abt, S. R., Potyondy, J. P. and Ryan, S. E., 2004, Measurement of coarse gravel and cobble transport using portable bedload traps, J. Hydraul. Eng., 130, pp. 879–893.

Chacho E. F., Burrows R. L., Emmett W. W., 1989, Detection of Coarse Sediment movement using radiotransmitters. In Proc. XXIII IAHR congress; pp. 367-373.

Einstein H. A., 1937, The bedload transport as probability problem. Mitteilung der Versuchsanstalt fuer Wasserbau an der Eidgenössischen Technischen Hochschule. Zürich; 110.

Emmett, W. W., 1980, A field calibration of the sediment trapping characteristics of the Helley-Smith bedload sampler, U. S. Geol. Surv. Prof. Pap., 1139, 44 p.

Ergenzinger P., Schmidt K.H., and Busskamp R., 1989, The Pebble Transmitter System (PETS): First Results of a Technique for Studying coarse Material Erosion, Transport and Deposition. Zeit. für Geomorphologie N.F. 33, pp. 503-508.

Gamnitzer, R., Lautenschläger, O. and Rupp, J. ,2006, ADMODUS – a sonic device for measuring bedload transport, internal report for viadonau.

Garcia, C., Laronne, J.B. and Sala, M., 2000,Continuous monitoring of bedload flux in a mountain gravel-bed river. Geomorphology, 34(1-2): pp. 23-31.

Gaudet, J. M., A. G. Roy, and Best, J. L., 1994, Effect of orientation and size of Helley-Smith sampler on its efficiency, J. Hydraul. Eng., 120, pp. 758– 766.

Habersack, H. M., H. P. Nachtnebel, and Laronne, J.B., 2001, The continuous measurement of bedload discharge in a large alpine gravel bed river, J. Hydraul. Res., 39, pp. 125– 133.

Habersack, H., 1998, Field measurements with the radio-telemetry system at the Angerbach and Wien River, internal report at the U. fuer Bodenkultur Vienna.

Habersack, H.M, 2001, Radio-tracking gravel particles in a large braided river in New Zealand: a field test of the stochastic theory of bedload transport proposed by Einstein, J. Hydrological Processes, Vol. 15/3, pp. 377-391.

Habersack, H.M. and Laronne, J. B., 2002, Evaluation and improvement of bedload discharge formulas based on Helley-Smith sampling in an alpine gravel bed river, J. Hydraulic Engineering, Vol. 128, No. 5, pp. 484-499.

Habersack, H.M. and Laronne, J.B., 2001, Bedload texture in an Alpine gravel bed river, Water Resources Research Vol. 37, No. 12, pp. 3359-3370.

Habersack, H.M., Seitz, H. and Laronne, J. B., 2008, Spatio temporal variability of bedload transport, J. Geodinamica Acta, (in print).

Hassan M. A., Church M., and Schick A. P., 1991. Distance of movement of coarse particles in gravel bed streams. Water Res. Res. 27: pp. 503-511.

Helley, E. J., and Smith, W., 1971, Development and calibration of a pressure-difference bedload sampler, open file report, Water Resour. Div., U. S. Geol. Surv., Menlo Park, Calif.

Hydrographic Service GmbH, 2006, ADMODUS measurements at the Austrian Danube River, report for viadonau.

Laronne J. B. and Duncan M. J., 1992, Bedload transport paths and gravel bar formation. In Dynamics of Gravel-bed rivers. Billi P, Hey RD, Thorne CR, Tacconi P (eds). John Wiley & Sons, pp. 177-202.

Laronne, J.B. & Cohen, H., 1998, Optimization of gravel mining and estimation of reservoir sedimentation rates in the south eastern coast of the Dead Sea. 2nd Annual Rpt Dead Sea Works Company (in Hebrew).

Laronne, J.B., Reid, I., Yitshak, Y. & Frostick, L.E., 1992, Recording bedload discharge in a semiarid channel, Nahal Yatir, Israel. IAHS publication No. 210, pp. 79 - 86.

Liedermann, M., 2007, Monitoring and modeling of river morphology and sediment transport, PhD at BOKU, in prep.

McEwan, I. K., Habersack, H.M. and Heald, J. G. C, 2001, Discrete particle modelling and active tracers: new techniques for studying sediment transport as a Lagrangian phenomenon, IN: M. Paul Mosley (ed.), pp. 339-368.

Mühlhofer, L., 1933, Untersuchungen über die Schwebstoff- und Geschiebeführung des Inn nächst Kirchbichl (Tirol), Die Wasserwirtschaft, Jahrgang 1933, Hefte 1 bis 6, 23 S.

Powell, M., Reid, I., Laronne, J.B. and Frostick, L., 1995, Cross-stream variability of bedload flux in narrow and wider ephemeral channels during desert flash floods, to appear in: GBR-IV publication.

Reid, I., Layman, J.T. and Frostick, L.E., 1980, The continuous measurement of bedload discharge. Journal of Hydraulic Research 18, pp. 243-249.

Rickenmann, D., Hofer, B. And Fritschi, B., 1997, Geschiebemessung mittels Hydrophon. Österreichische Wasser- und Abfallwirtschaft, 49(11/12), pp. 219-228.

Sayre W.W. and Hubbell D.W., 1965, Transport and dispersion of labeled bed material, North Loup River, Nebraska. U.S. Geol. Survey. Prof. Paper 433-C.

Seitz, H., 2007, Automatic bedload monitoring at the Drau River, PhD at BOKU, in prep.

Smart, GM, Habersack, HM, 2007, Pressure fluctuations and gravel entrainment in rivers, J. Hydraulic Research, Vol: 45 / Issue: 5, pp. 661–673.

Stelczer K., 1971, Description of bedload movement in terms of probability theory. Vizügyi Közlemenyek 4 (in Hungarian).

Stelczer K., 1981, Bedload transport: theory and practice. Water Resources Publications: Littleton, Colorado.

Sterling, S. M., and M. Church, 2002, Sediment trapping characteristics of a pit trap and the Helley-Smith sampler in a cobble gravel bed river, Water Resour. Res., 38(8), 1144, doi:10.1029/2000WR000052.

Vericat, D., M. Church, and R. J. Batalla, 2006, Bedload bias: Comparison of measurements obtained using two (76 and 152 mm) Helley-Smith samplers in a gravel bed river, Water Resour. Res., 42, W01402, doi:10.1029/2005WR004025.